The minimal curvaton-higgs (MCH) model

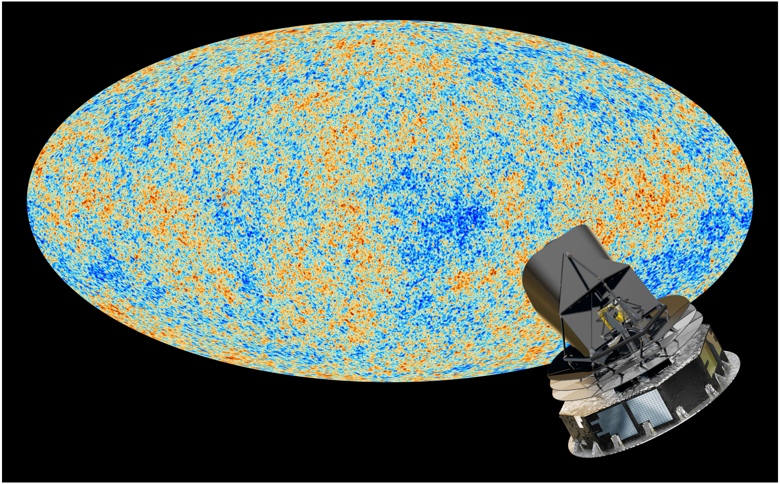
Rose Lerner

Based on: Kari Enqvist, RL, Tomo Takahashi [arXiv:1310.1374]
Kari Enqvist, RL, Stanislav Rusak [arXiv:1308.3321]
Kari Enqvist, Daniel Figueroa, RL [arXiv:1211.5028]
Kari Enqvist, RL, Olli Taanila, Anders Tranberg [1205.5446]
RL, Scott Melville, [1402.3176]
RL, Anders Tranberg [to appear]

rose.lerner@desy.de
DESY, Hamburg
October 2014

Overview

CMB perturbations



CMB perturbations

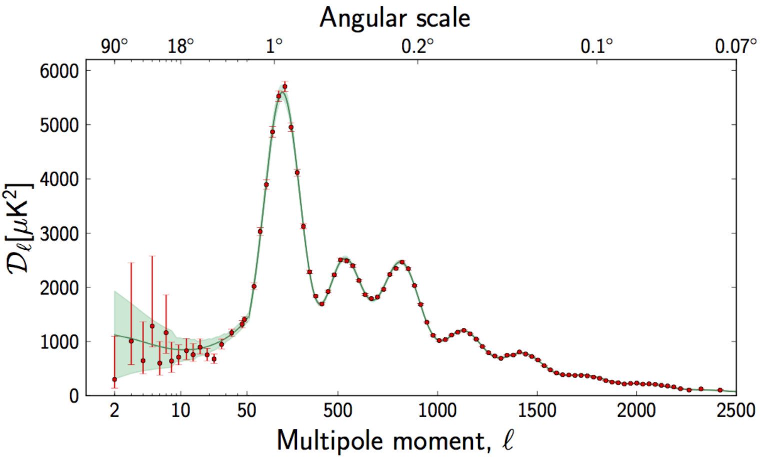


Figure from the Planck collaboration.

What does a complete cosmological model require?

Observational:

- inflation
- perturbations: ζ, n, r, $f_{NL}\ldots$
- reheating
- dark matter
- baryogenesis
- ...

What does a complete cosmological model require?

Observational:

- inflation
- perturbations: ζ, n, r, $f_{NL}\dots$
- reheating
- dark matter
- baryogenesis
- ...

Theoretical:

- specify all fields in the theory
- consider all interactions
- quantum corrections
- explain initial conditions
- ...

What does a complete cosmological model require?

Observational:

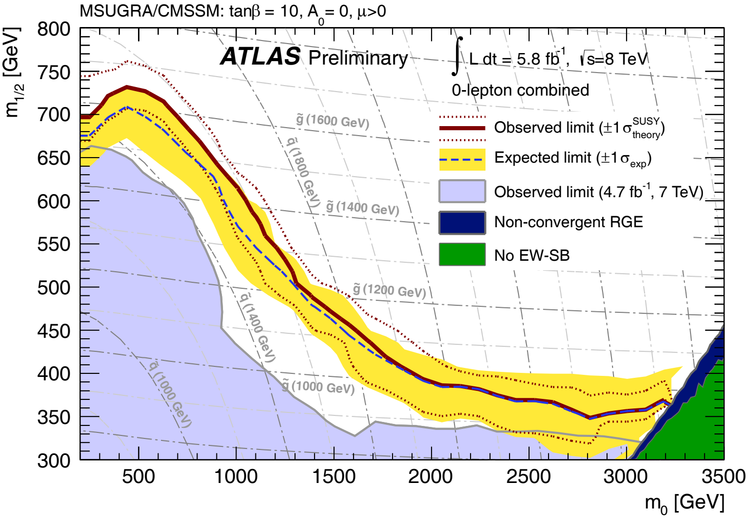
- inflation
- perturbations: ζ, n, r, $f_{NL}\dots$
- reheating
- dark matter
- baryogenesis
- ...

Theoretical:

- specify all fields in the theory
- consider all interactions
- quantum corrections
- explain initial conditions
- ...

Minimal extensions to the standard model allow precise calculations of cosmological processes

Where is SUSY?



What is a curvaton model?

Single field inflaton:

A single field ϕ both drives inflation and is the source of the perturbations.

What is a curvaton model?

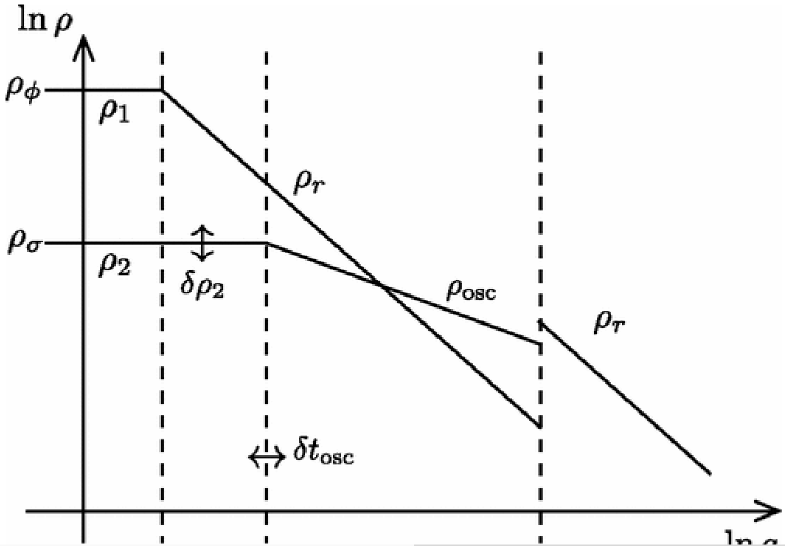
Single field inflaton:

A single field ϕ both drives inflation and is the source of the perturbations.

Curvaton paradigm:

One field ϕ drives inflation but has negligible perturbations; a second field σ is the source of perturbations but is negligible during inflation.

Energy densities in the curvaton paradigm



Why study curvaton models?

- because they exist!

Why study curvaton models?

- because they exist!
- because they can give measurable non-Gaussianity and isocurvature

Why study curvaton models?

- because they exist!
- because they can give measurable non-Gaussianity and isocurvature
- because light scalar fields ($m < H$) might exist and it is important to calculate their consequences

Why study curvaton models?

- because they exist!
- because they can give measurable non-Gaussianity and isocurvature
- because light scalar fields ($m < H$) might exist and it is important to calculate their consequences
- because the curvaton mechanism gives more freedom for the inflation model

Why study curvaton models?

- because they exist!
- because they can give measurable non-Gaussianity and isocurvature
- because light scalar fields $(m < H)$ might exist and it is important to calculate their consequences
- because the curvaton mechanism gives more freedom for the inflation model
- because they have interesting, constrainable dynamics after inflation

The minimal curvaton-higgs (MCH) model

MCH Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{\lambda}{4!}\sigma^4 + \frac{1}{2}g^2\sigma^2\Phi^\dagger\Phi$$

The minimal curvaton-higgs (MCH) model

MCH Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{\lambda}{4!}\sigma^4 + \frac{1}{2}g^2\sigma^2\Phi^\dagger\Phi$$

- assume $\sigma \to -\sigma$ symmetry
- assume $\lambda = 0$
- assume instant inflaton decay
- free parameters: $g, m_\sigma, H_*, \sigma_*$

Consequences of coupling g

- correction to $V(\sigma)$

$$\Delta V(\sigma) = \frac{\left(g^2\sigma^2 + m_h^2\right)^2}{64\pi^2} \log\left(\frac{g^2\sigma^2 + m_h^2}{\mu^2}\right)$$

[choose $\mu = m_h = 126$ GeV]

Consequences of coupling g

- correction to $V(\sigma)$

$$\Delta V(\sigma) = \frac{\left(g^2\sigma^2 + m_h^2\right)^2}{64\pi^2} \log\left(\frac{g^2\sigma^2 + m_h^2}{\mu^2}\right)$$

[choose $\mu = m_h = 126$ GeV]

- σ can feel any thermal background of Higges

$$m_\sigma^2 \to m_\sigma^2 + \frac{1}{12} g^2 T^2$$

Consequences of coupling g

- correction to $V(\sigma)$

$$\Delta V(\sigma) = \frac{\left(g^2\sigma^2 + m_h^2\right)^2}{64\pi^2} \log\left(\frac{g^2\sigma^2 + m_h^2}{\mu^2}\right)$$

  [choose $\mu = m_h = 126$ GeV]
- σ can feel any thermal background of Higges

$$m_\sigma^2 \to m_\sigma^2 + \frac{1}{12} g^2 T^2$$

- homogeneous σ can decay: $\Gamma_{eff} = \Gamma_{NP} + \Gamma_{pert} + \Gamma_5$
  1. non-perturbative decay
  2. perturbative scattering with thermal bath
  3. dimension-5 operators

Decay 1: non-perturbative decay

Summary

- after inflation, higgs is thermalised and gains large thermal mass $\propto g_T T$, where $g_T^2 = 0.1$
- curvaton couples to higgs and could also get a thermal mass
- these thermal masses block resonant preheating until T falls

Decay 1: Broad and narrow resonances

- After inflation, usually in broad resonance regime, $q(t) = \left(\frac{g\Sigma(t)}{2m_\sigma}\right)^2 \gg 1$
- We found that the broad resonance is almost always blocked
- Curvaton amplitude $\Sigma(t)$ decreases and we eventually reach narrow resonance region with $q \ll 1$
- narrow resonance is a continuous process; excites modes within a thin momentum band
- this is where we start our (outline) calculation
- assume we have already calculated the decaying $\Sigma(t)$ and form of oscillations in the relevant background.

Decay 1: The narrow resonance

- Higgs equation of motion:
$$\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$$

Decay 1: The narrow resonance

- Higgs equation of motion:
  $\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$
- conservation of energy: $2m_\sigma = 2E(k)$

Decay 1: The narrow resonance

- Higgs equation of motion:
$\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$
- conservation of energy: $2m_\sigma = 2E(k)$
- energy of produced higgs:
$E(k) = \frac{k^2}{a^2} + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2$

Decay 1: The narrow resonance

- Higgs equation of motion:
$\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$
- conservation of energy: $2m_\sigma = 2E(k)$
- energy of produced higgs:
$E(k) = \frac{k^2}{a^2} + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2$
- Require: $g_T^2 T^2 + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) \leq m_\sigma^2$

Decay 1: The narrow resonance

- Higgs equation of motion:
  $\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$
- conservation of energy: $2m_\sigma = 2E(k)$
- energy of produced higgs:
  $E(k) = \frac{k^2}{a^2} + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2$
- Require: $g_T^2 T^2 + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) \leq m_\sigma^2$
- Remember that $q \ll 1$

Decay 1: The narrow resonance

- Higgs equation of motion:
  $\ddot{\phi}_\alpha + 3H\dot{\phi}_\alpha + \left(\frac{k^2}{a^2} + g^2\Sigma^2(t)\sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2\right)\phi_\alpha = 0$
- conservation of energy: $2m_\sigma = 2E(k)$
- energy of produced higgs:
  $E(k) = \frac{k^2}{a^2} + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) + g_T^2 T^2$
- Require: $g_T^2 T^2 + 4q(t)m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) \leq m_\sigma^2$
- Remember that $q \ll 1$
- Thus, narrow resonance can only occur for $T \leq \frac{m_\sigma}{g_T}$

Decay 1: Thermal blocking

From previous slide

$$g_T^2 T^2 + 4q(t) m_\sigma^2 \sin^2\left(m_\sigma t + \frac{\pi}{8}\right) \leq m_\sigma^2$$

Notes

- If the higgs had no coupling to the thermal background ($g_T = 0$), then there would be no blocking of the resonance!
- Rate of energy transfer typically very slow
- Thermal blocking typically lasts for a huge number of oscillations
- The curvaton's thermal mass modifies $\Sigma(t)$ (see paper)
- Without thermal blocking, the curvaton would quickly disappear and may not be a good curvaton candidate

Decay 2: perturbative scattering with thermal bath

Simple calculation:

$$\Gamma_{pert} = \frac{1}{576\pi} \frac{g^4 T^2}{m_\sigma(T)}$$

Decay 2: perturbative scattering with thermal bath

Simple calculation:

$$\Gamma_{pert} = \frac{1}{576\pi}\frac{g^4 T^2}{m_\sigma(T)}$$

- process efficient at $\Gamma(t) \geq H(t)$
- $H \propto T^2$
- so if $m_\sigma(T) = m_\sigma$, occurs immediately or never!
- if $m_\sigma(T) = \frac{1}{\sqrt{12}} g T$, efficient process if

$$g \geq 4.9 g_*^{1/8} \left(\frac{m_\sigma}{M_{Pl}}\right)^{1/4}$$

Decay 2: perturbative scattering with thermal bath

Simple calculation:

$$\Gamma_{pert} = \frac{1}{576\pi}\frac{g^4 T^2}{m_\sigma(T)}$$

- this is a very simple calculation
- ignores e.g. fact that momenta are soft
- many recent papers give improvement e.g. Mukaida, Nakayama,Takimoto [1308.4394]

Decay 3: dimension-5 operators

Example dimension-5 coupling:

$$\mathcal{L}_5 \propto \frac{1}{M_P} \sigma \bar{f} \Phi f$$

Gives:

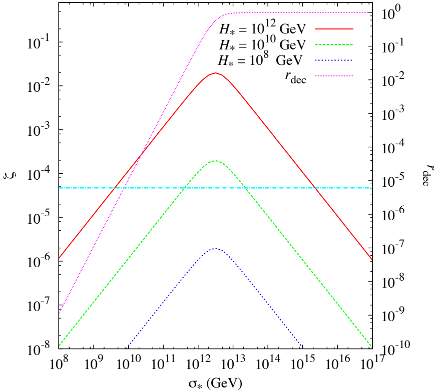
$$\Gamma_5 \approx \frac{m_\sigma^3}{M_P^2}$$

Other constraints

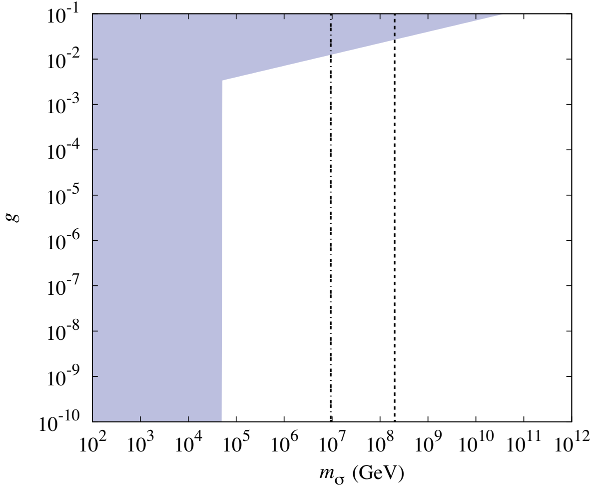
- big bang nucleosynthesis (BBN)
  - neutrinos decouple at 4 MeV
  - avoid spoiling BBN if curvaton decay occurs before this
  - requires $m_\sigma > 8 \times 10^4$ GeV
- dark matter
  - isocurvature if dark matter freezes out before curvaton decay
  - large isocurvature is ruled out by WMAP and Planck
  - standard WIMP scenario with decoupling at $T = 10$ GeV gives $\Gamma > 10^{-16}$ GeV
  - from Γ_5, we get $m_\sigma = 10^7$ GeV

Methodology

- split into two solutions
- include full $V = V_0 + \Delta V + V(T)$
- numerically follow oscillations
- use scaling law evolution between transitions
- use δN formalism to obtain ζ, f_{NL} and g_{NL}

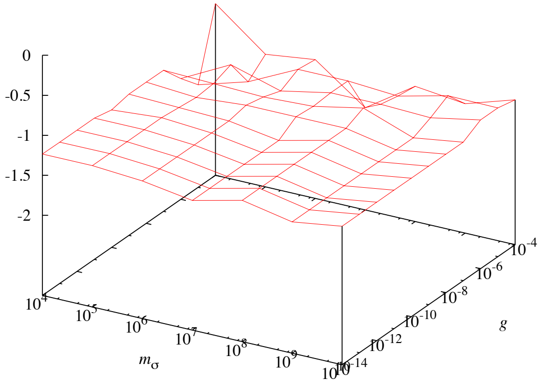


Parameter space for large σ_*



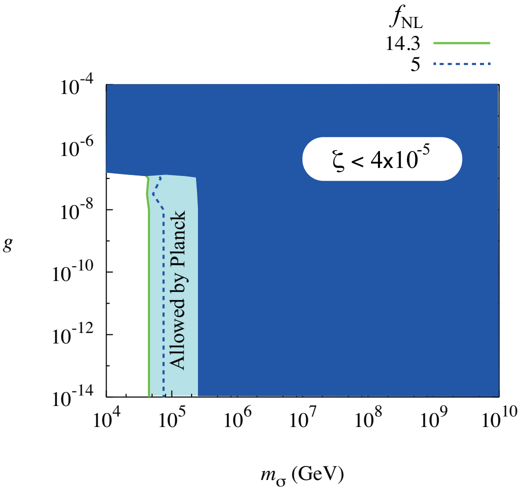
- white is allowed
- $m_\sigma < H_*$ not shown
- ΔV not included

f_{NL} for large σ_*



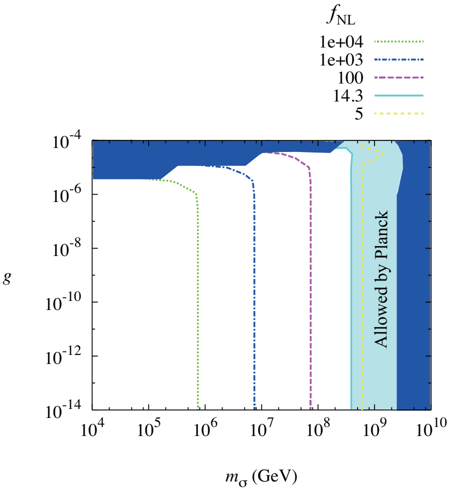
- $H_* = 10^{12}$ GeV

Constraints including f_{NL} for small σ_*



- pale blue is allowed
- $H_* = 10^9$ GeV

Constraints including f_{NL} for small σ_*



- pale blue is allowed
- $H_* = 10^{11}$ GeV

Remaining unknowns are (in principle!) calculable

Including:

- numerical (lattice) consideration of thermal blocking
- baryogenesis
- dark matter
- running of coupling constant and other quantum corrections
- spectral index n and tensor-to-scalar ratio r, once inflaton specified
- ...
- value of initial condition (?)

Thermal blocking on the lattice (PRELIMINARY!)

- Is the analytical analysis of thermal blocking sufficient?

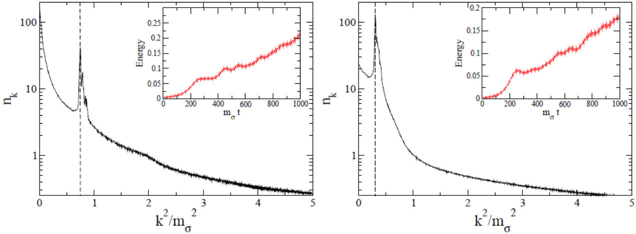


Figure 1: The (log of) the particle number after preheating for $m_\sigma t = 1000$, corresponding to approximately 160 inflaton oscillations. Inset is the energy in the preheated field(s). The Higgs field is self-interacting and coupled to the "by-hand" inflaton, but has no coupling to any other fields. Without an additional mass (left), and with a mass of $M^2 = 0.5m_\sigma^2$ (right)

Thermal blocking on the lattice (PRELIMINARY!)

- Is the analytical analysis of thermal blocking sufficient?
- Preliminary results say "yes"

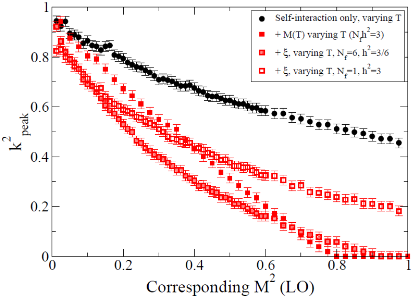


Figure 3: The position of the resonance peaks as a function of the corresponding effective (LO) mass, when varying T. Filled symbols: With the leading order effective mass and Higgs self-interaction. Open symbols: Interacting with full dynamical light fields. Shaded symbols: Interacting with $N_f = 6$ full dynamical light fields.

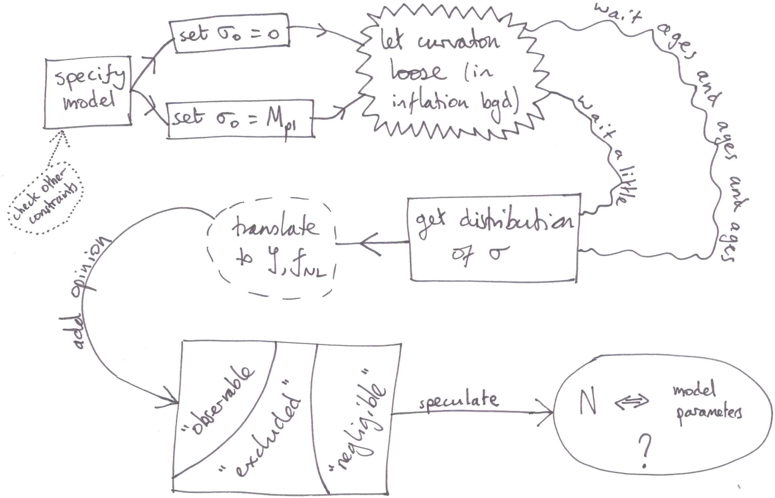
The questions

1. if (non-inflaton) scalar fields exist in a theory, do they either rule out the theory or otherwise affect observational predictions?
2. if we design a curvaton model, does this have natural or fine-tuned initial conditions?

Initial Condition

The curvaton field value σ_* when observable scales exit the horizon determines the observational predictions
(given model parameters).

We did this:


specify model
set $\sigma_0 = 0$
set $\sigma_0 = M_{pl}$
let curvaton loose (in inflation bgd)
wait ages and ages and ages
wait a little
get distribution of σ
translate to ζ, f_{NL}
check other constraints
add opinion
"observable"
"excluded"
"negligible"
speculate
N ⟺ model parameters
?

Specify model: minimal curvaton-higgs (MCH)

Reminder: MCH Lagrangian

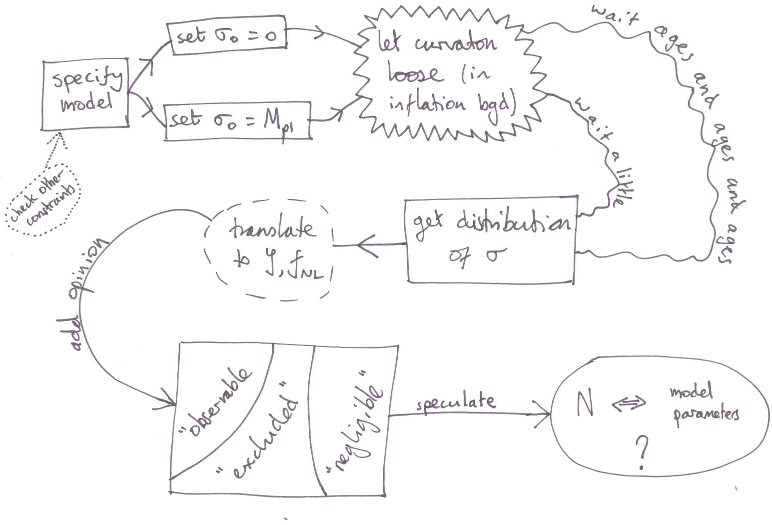
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{\lambda}{4!}\sigma^4 + \frac{1}{2}g^2\sigma^2\Phi^\dagger\Phi$$

Specify model: effective mass from the Higgs

- during inflation, curvaton gets a contribution to effective mass from interaction with higgs
- $m_{eff}^2 = m_\sigma^2 + \frac{1}{2} g^2 h_*^2$
- after inflation the higgs contribution quickly disappears

Two regimes:

1. $gh_* \gg m_\sigma$: g determines m_{eff}, m_σ determines Γ_{eff}
2. $gh_* \ll m_\sigma$: m_σ determines both


specify model
set $\sigma_0 = 0$
set $\sigma_0 = M_{pl}$
let curvaton loose (in inflation bgd)
wait ages and ages and ages and ages
wait a little
get distribution of σ
translate to ζ, f_{NL}
check other constraints
add opinion
"observable"
"excluded"
"negligible"
speculate
N ⟺ model parameters
?

Interpretation of $P(\sigma)$

1. set up background inflation
2. add a curvaton
3. curvaton experiences slow roll and random quantum kicks
4. find value of σ_* in our patch
5. run the simulation many times
6. plot final σ_* from all runs — this is $P(\sigma)$

The distribution of σ_*

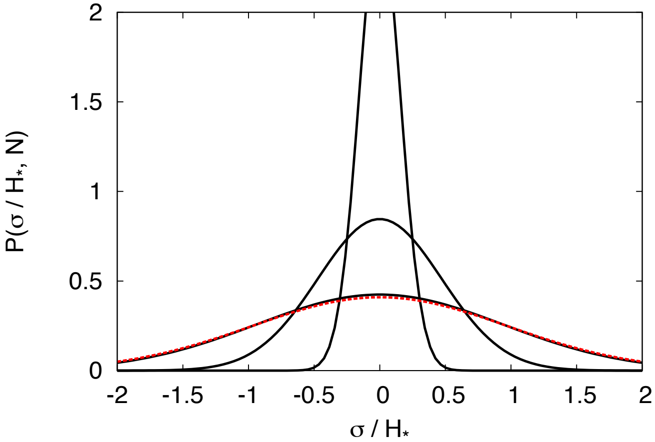
Fokker-Planck equation

$$\dot{P}(\sigma, N) = \frac{1}{3H_*^2} V''(\sigma) P(\sigma, N) + \frac{1}{3H_*^2} V'(\sigma) P'(\sigma, N) + \frac{H_*^2}{8\pi^2} P''(\sigma, N)$$

Derivation:

- Integrate out short wavelength modes with $k \gg H_*$
- Langevin equation $\dot{\sigma} = \frac{V'(\sigma)}{3H_*} + \xi(t)$
- random Gaussian noise: $\langle \xi(t) \xi(t') \rangle = \delta(t - t') \frac{H_*^3}{8\pi^2}$

Evolution of $P(\sigma, N)$ for $V(\sigma) = \frac{1}{2} m_{eff}^2 \sigma^2$



$(N = 1, 10, 100;\ m_{eff} = 0.2 H_*;\ \sigma_0 = 0.)$

Solution for quadratic potential $V(\sigma) = \frac{1}{2} m_{eff}^2 \sigma^2$

$$P(\sigma, N) = \frac{1}{\sqrt{2\pi w^2(N)}} \exp\left(-\frac{(\sigma - \sigma_c(N))^2}{2H_*^2 w^2(N)}\right)$$

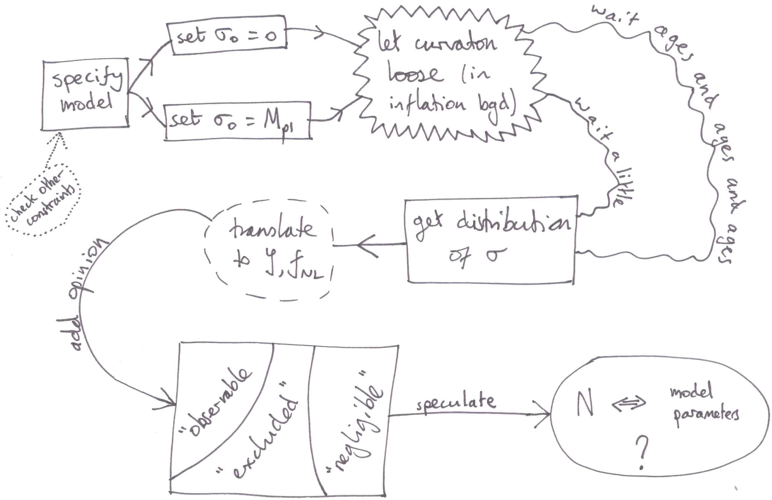
where

$$\sigma_c(N) = \sigma_c(0) \exp\left(-\frac{m_{eff}^2}{3H_*^2} N\right)$$

and

$$w^2(N) = \frac{3H_*^2}{8\pi^2 m_{eff}^2} - \left(\frac{3H_*^2}{8\pi^2 m_{eff}^2} - \frac{w^2(0)}{H_*^2}\right) \exp\left(-\frac{2m_{eff}^2}{3H_*^2} N\right)$$

- initial central value of the distribution: $\sigma_c(0) \equiv \sigma_0$
- initial width: $w(0)$


specify model
set $\sigma_0 = 0$
set $\sigma_0 = M_{pl}$
let curvaton loose (in inflation bgd)
wait ages and ages and ages and ages
wait a little
get distribution of σ
translate to ζ, f_{NL}
check other constraints
add opinion
"observable"
"excluded"
"negligible"
speculate
N ⟺ model parameters
?

Translate to ζ: valid for $V(\sigma) = \frac{1}{2} m_{eff}^2 \sigma^2$

- Probability distribution of ζ given by

$$P(\zeta, N) = P[\sigma_*^-, N] \left| \frac{d\sigma_*}{d\zeta} \right|_{\sigma_*^-} + P[\sigma_*^+, N] \left| \frac{d\sigma_*}{d\zeta} \right|_{\sigma_*^+}$$

- ... resulting in

$$P(\zeta, N) = \frac{1}{\sqrt{2\pi w^2(N)}} \exp\left(- \frac{\left(\left[\frac{H_*}{6\pi\zeta} (1 - Y(\zeta)) \right] - \sigma_c(N) \right)^2}{2 H_*^2 w^2(N)} \right) \frac{H_*(1 - Y(\zeta))}{6\pi\zeta^2 Y(\zeta)}$$
$$+ \frac{1}{\sqrt{2\pi w^2(N)}} \exp\left(- \frac{\left(\left[\frac{H_*}{6\pi\zeta} (1 + Y(\zeta)) \right] - \sigma_c(N) \right)^2}{2 H_*^2 w^2(N)} \right) \frac{H_*(1 + Y(\zeta))}{6\pi\zeta^2 Y(\zeta)}$$

- $Y(\zeta) \equiv \sqrt{1 - \frac{288\pi^2 M_{Pl} m_\sigma \zeta^2}{H_*^2}}$
- ... and something similar for f_{NL}.

Add opinion: defining "observable", "negligible" and "excluded"

As working definitions, we take:

observable

$0.1\zeta_{WMAP} \leq \zeta \leq \zeta_{WMAP}$ or $5 < f_{NL} < 14.3$

negligible

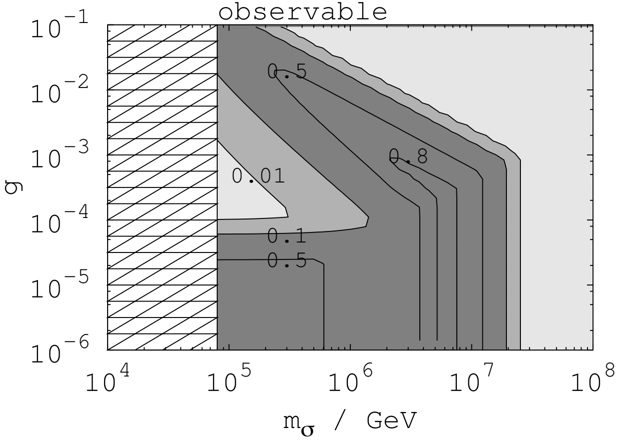
$\zeta < 0.1\zeta_{WMAP}$ and $f_{NL} < 5$

excluded

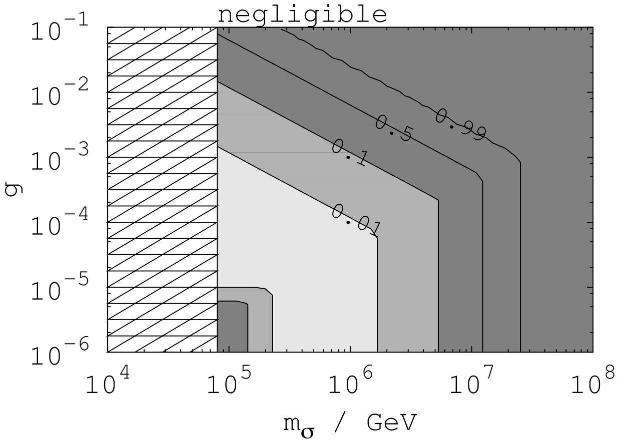
$\zeta > \zeta_{WMAP}$ or $f_{NL} > 14.3$

- Note that we must integrate over ζ to obtain $P(0.1\zeta_{WMAP} < \zeta_{curvaton} < \zeta_{WMAP})$

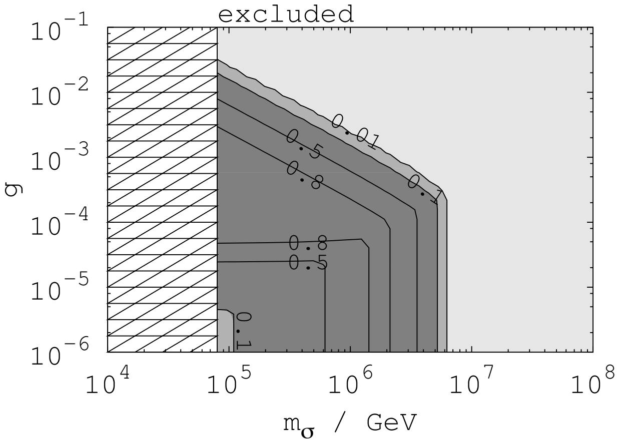
Wait ages and ages: $P(observable)$



Wait ages and ages: $P(negligible)$

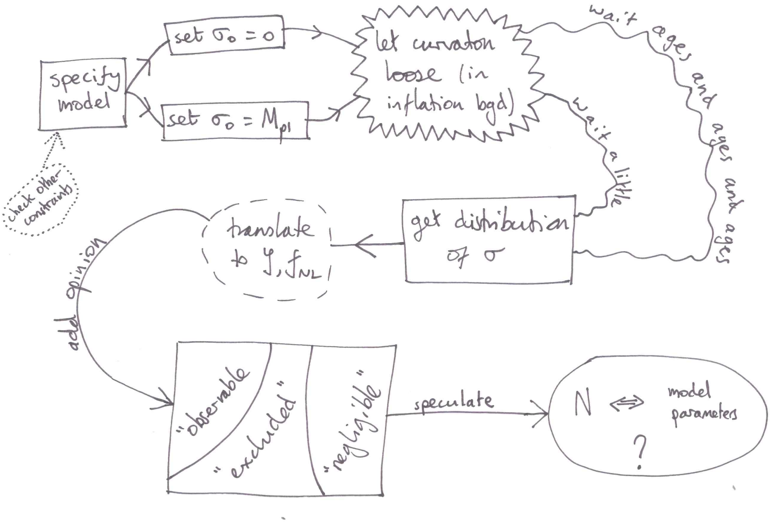


Wait ages and ages: $P(excluded)$

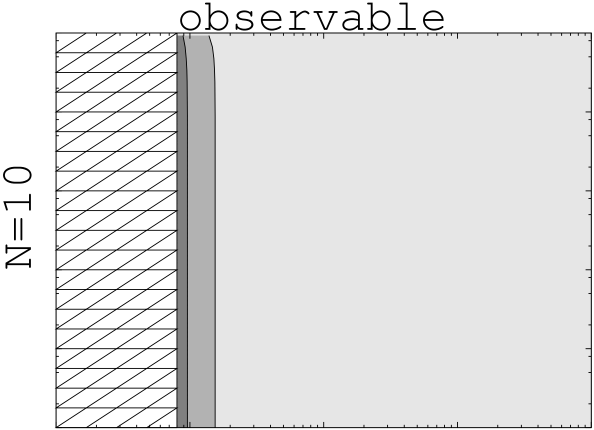


Wait just a little

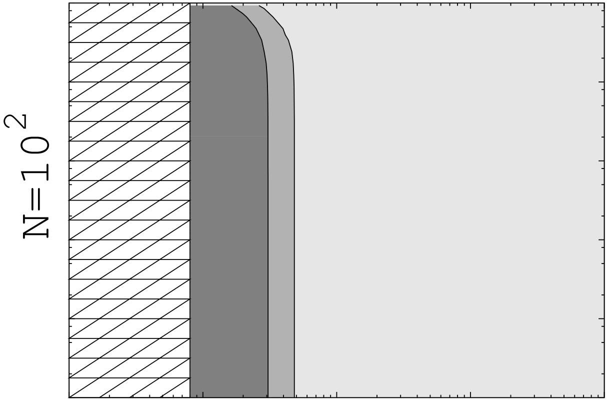
- ζ is calculated when the perturbations leave the horizon, about 60 e-foldings before the end of inflation
- the N shown here is the number of e-foldings before horizon exit
- timescale to reach equilibrium given by $N_{dec} = \frac{3H_*^2}{2m_\sigma^2}$
- N_{dec} can be large


specify model
set $\sigma_0 = 0$
set $\sigma_0 = M_{pl}$
let curvaton loose (in inflation bgd)
wait ages and ages and ages and ages
wait a little
get distribution of σ
translate to ζ, f_{NL}
check other constraints
add opinion
"observable"
"excluded"
"negligible"
speculate
N ⟺ model parameters
?

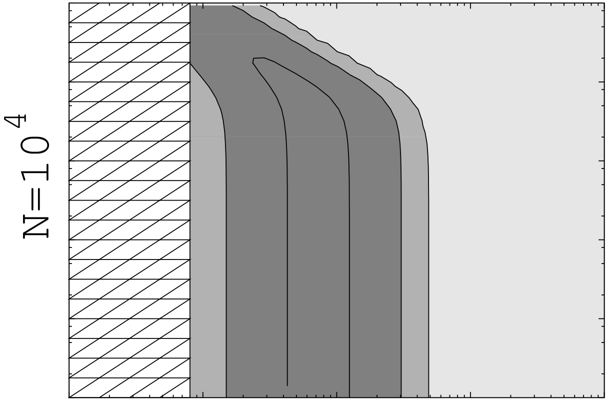
$P(observable)$ for $\sigma_0 = 0$; $N = 10$



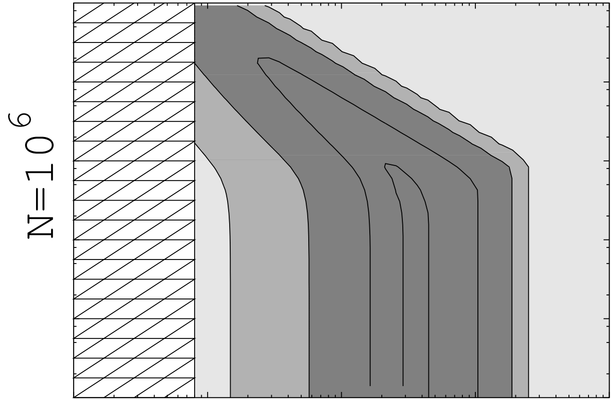
$P(observable)$ for $\sigma_0 = 0$; $N = 10^2$



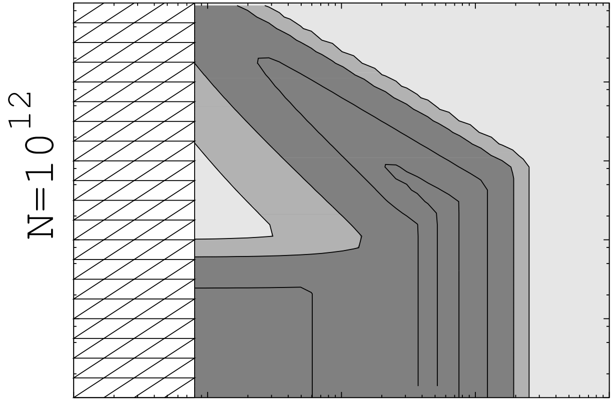
$P(observable)$ for $\sigma_0 = 0$; $N = 10^4$



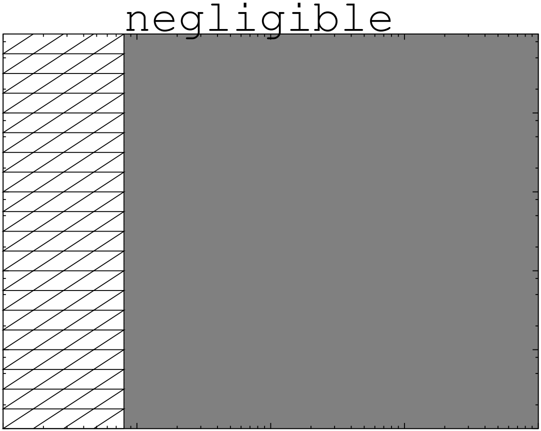
$P(observable)$ for $\sigma_0 = 0$; $N = 10^6$



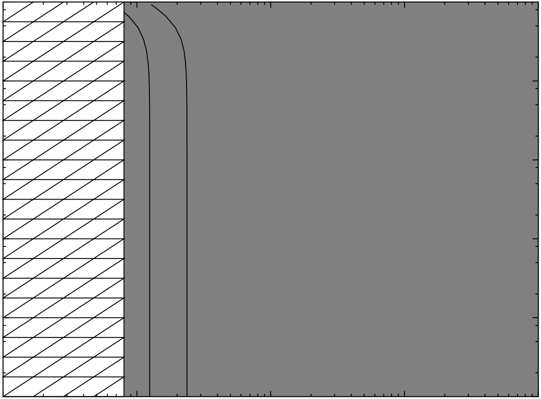
$P(observable)$ for $\sigma_0 = 0$; $N = 10^{12}$



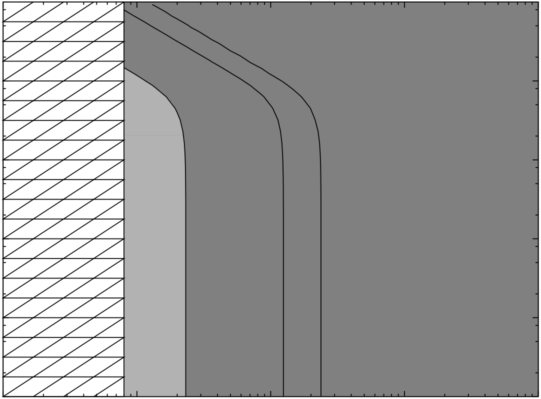
$P(negligible)$ for $\sigma_0 = 0$; $N = 10$



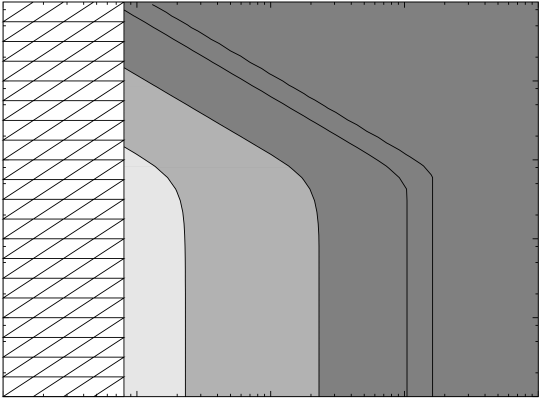
$P(negligible)$ for $\sigma_0 = 0$; $N = 10^2$



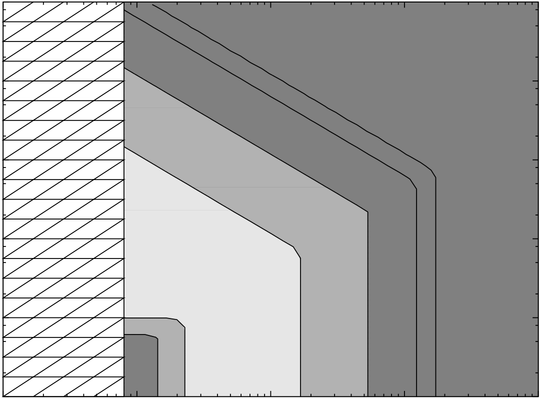
$P(negligible)$ for $\sigma_0 = 0$; $N = 10^4$



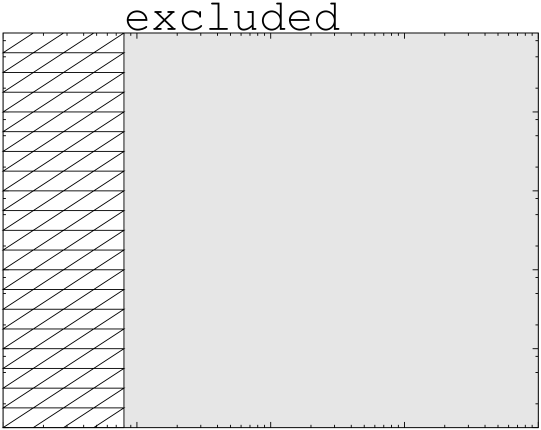
$P(negligible)$ for $\sigma_0 = 0$; $N = 10^6$



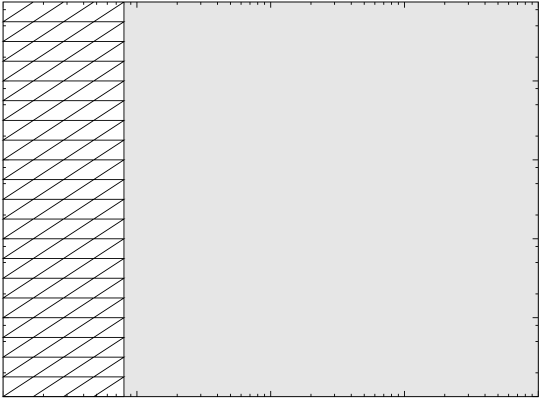
$P(negligible)$ for $\sigma_0 = 0$; $N = 10^{12}$



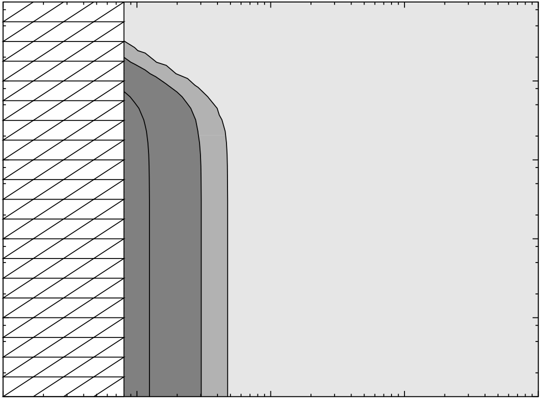
$P(excluded)$ for $\sigma_0 = 0$; $N = 10$



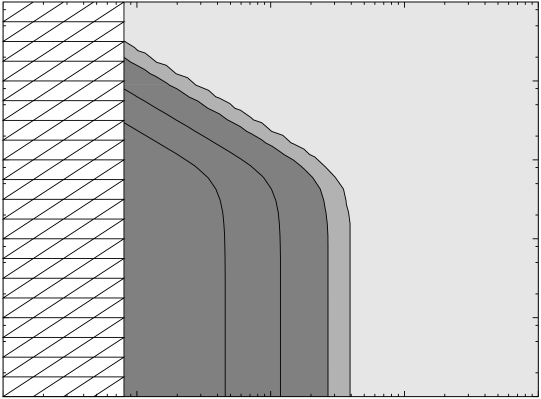
$P(excluded)$ for $\sigma_0 = 0$; $N = 10^2$



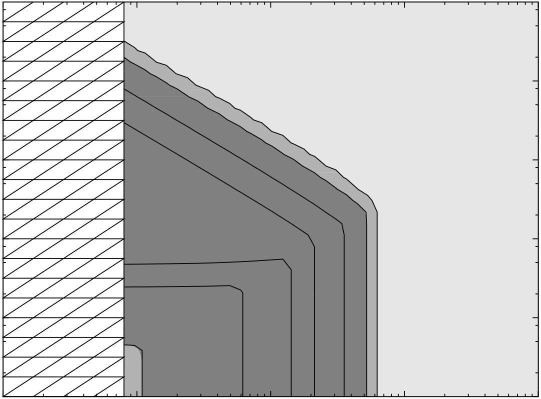
$P(excluded)$ for $\sigma_0 = 0$; $N = 10^4$

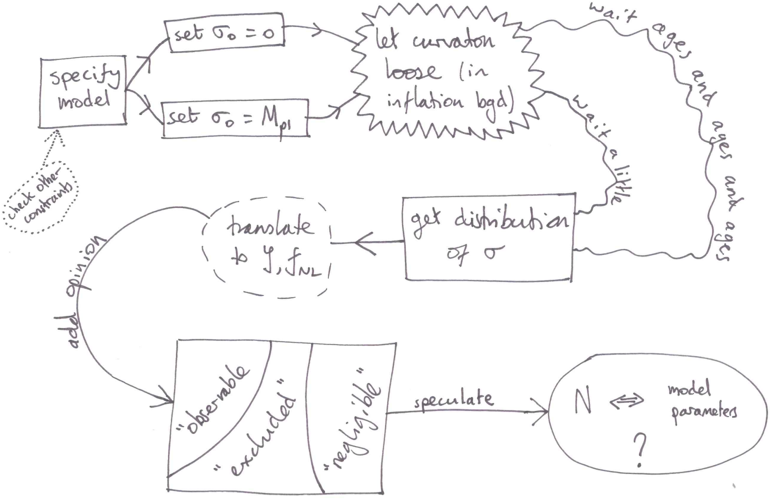


$P(excluded)$ for $\sigma_0 = 0$; $N = 10^6$

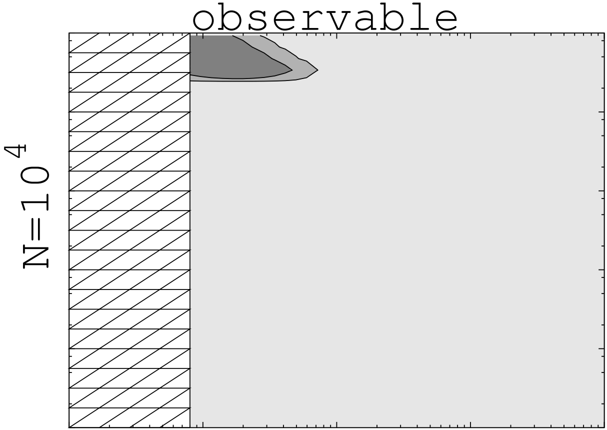


$P(excluded)$ for $\sigma_0 = 0$; $N = 10^{12}$

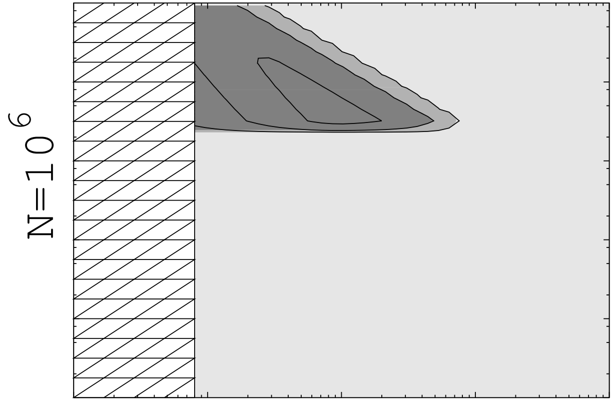



specify model
set σ₀ = 0
set σ₀ = M_pl
let curvaton loose (in inflation bgd)
wait ages and ages and ages
wait a little
get distribution of σ
translate to ζ, f_NL
add opinion
"observable"
"excluded"
"negligible"
speculate
N ⟺ model parameters
?
check other constraints

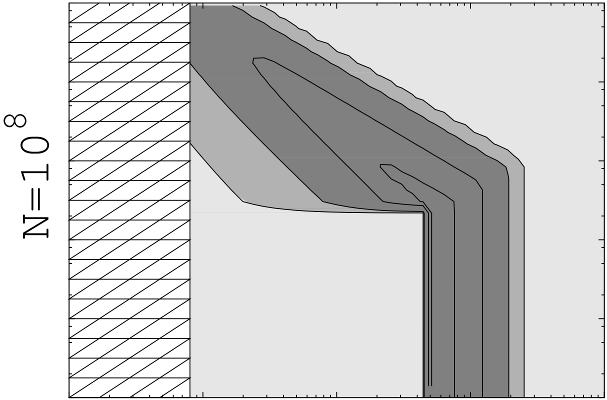
$P(observable)$ for $\sigma_0 = M_P$; $N = 10^4$



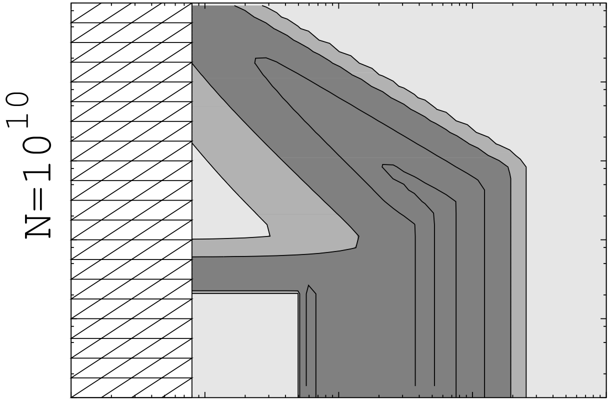
$P(observable)$ for $\sigma_0 = M_P$; $N = 10^6$



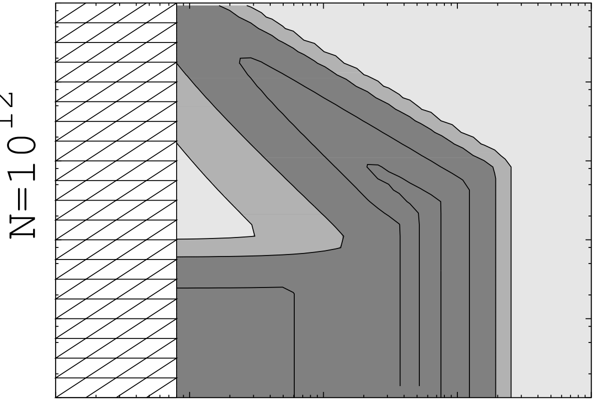
$P(observable)$ for $\sigma_0 = M_P$; $N = 10^8$



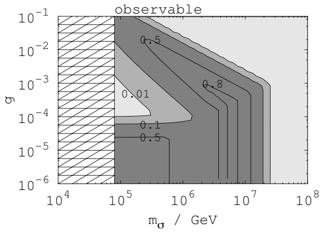
$P(observable)$ for $\sigma_0 = M_P$; $N = 10^{10}$



$P(observable)$ for $\sigma_0 = M_P$; $N = 10^{12}$



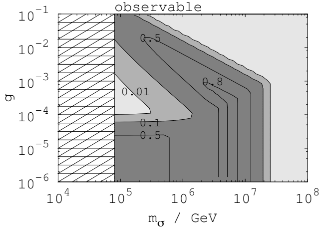
Notes



- "probable" regions of parameter space exist for some range of model parameters

- large masses $m_\sigma > 2 \times 10^7$ GeV are (dis)favoured
- $m_\sigma < 8 \times 10^4$ GeV are excluded due to a late curvaton decay
- results valid for $g < (m_\sigma / M_P)^{1/4}$
- very little dependence on the initial conditions for large effective mass $m_{eff}^2 = m_\sigma^2 + g^2 h_*^2$
- scalars with certain properties should not be

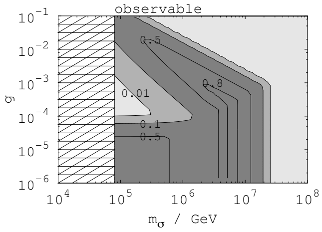
Speculate: new observations



New information?

- tensor-to-scalar ratio $r \rightarrow H_*$
- Planck $\rightarrow f_{NL}$
- Planck $\rightarrow$ spectral index n_s $\rightarrow$ constrains g and m_σ (once V_{inf} specified)
- WIMP dark matter detection $\rightarrow$ increased lower bound on m_σ

Speculate: linking N, g and m_σ

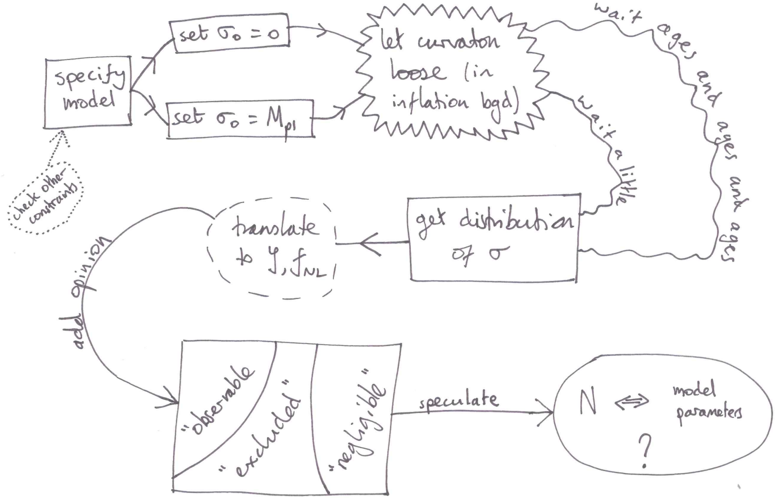


- if large m_σ favoured, would need very large N.
- if small m_σ and large g was instead favoured, $N = \mathcal{O}(10 - 100)$ would be sufficient, if $\sigma_0 = 0$ justified.
- Conversely, knowledge from fundamental theories about N could give information about m_σ and g.

The questions

1. if (non-inflaton) scalar fields exist in a theory, do they either rule out the theory or otherwise affect observational predictions?
2. if we design a curvaton model, does this have natural or fine-tuned initial conditions?

See also arxiv/1402.3176



The MCH model: summary

- MCH model is standard model + one real scalar curvaton
- non-perturbative decay into higgses is thermally blocked
- decay via dimension-5 operators determines predictions
- BBN, DM and interactions with the thermal background impose constraints
- distribution of initial field value σ_* could be determined under assumptions
- scalars with certain properties should not be ignored as possible curvatons!